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Hierarchical environmental risk mapping of material degradation in historic masonry buildings: An integrated approach considering climate change and structural damage

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HIGHLIGHTS

- Resilience of cultural heritage to climate change requires multidisciplinarity.
- New method for material degradation risk mapping in masonry buildings is proposed.
- Structural-thermal models and field tests are used to study climate change hazard.
- Interactions between climate change and structural damage are highlighted.
- Application to the Consoli Palace provides priorities of intervention on the façade.

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ABSTRACT

Resilience of new and existing buildings to climate change is a key research issue. Climate change-related phenomena can considerably affect buildings mechanical and thermal-energy response by contributing to materials degradation and structural safety. Such an impact is even further exacerbated in historical constructions, more vulnerable to such events due to their ancient structure if compared to recent designs. The purpose of this paper is to propose an innovative, integrated, multidisciplinary methodology for assessing construction materials' degradation in historic masonry buildings and its potential future evolution, providing a risk mapping accounting for interactions between climate change effects and structural damage. Such a replicable approach consists in (i) preliminary site inspections, (ii) damage and degradation surveys, (iii) development and calibration of numerical models predicting structural-thermal response and (iv) prediction of materials degradation accounting for future climate conditions and potential worsening of structural damage. The final output of the procedure is a hierarchical mapping of regions with different degradation severities, by identifying those where a specific type of degradation or damage insists but are likely stable and those where they are expected to get worse due to changes in future climate conditions or to a negative interaction between degradation and damage. The presented approach is applied to an iconic Italian monumental building, the Consoli Palace in Gubbio, where future climate scenarios up to 2080 are simulated according to the IPCC climate change predictions. Results highlight that thermal-energy and structural aspects need to be jointly considered in the preservation of surface materials of historic buildings exposed to climate change severity.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) [1,2] confirmed non-negligible climate change phenomena and an unequivocal warming mainly generated by the increasing rate of anthropogenic greenhouse gas emissions. Such acknowledged near-term climate change events were demonstrated to seriously affect pathologies of historical buildings and, particularly, degradation of materials of external façades [3]. The effect of climate change is acknowledged to be particularly exacerbated in the case of heritage buildings because these are typically low-performance

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buildings characterized by (i) a weak and ancient structure, (ii) old construction techniques, and (iii) ineffective if not lacking HVAC systems [4]. Therefore, special efforts should be dedicated to the preservation of historical constructions to face the upcoming climate change events by implementing strategies which do not affect the architectural quality of the ancient structures according to local regulations.

Climate change can negatively act on heritage built environment in several ways [5–7]. Among the various material degradation mechanisms associated to climate change, excessive rainfalls play a major role in causing surface recessions of stone [8], as well as surface erosion and surface strength reduction [9]. Moisture content is a critical parameter affecting ageing and durability of fabric materials of historic buildings, with obvious consequences in terms of climate change related effects on heritage preservation. In this regards, environmental monitoring is a must for a reliable analysis of the building performance under changing climatic conditions [10]. Humidity is another significant driver of degradation phenomena, that can interact with air pollution in causing degradation of limestone in historical buildings [11,12]. Climate change also affects the frequency of occurrence of freezing-thaw cycles [13] that produce mechanical stress on masonry surfaces, causing surface degradation.

Literature counts several applications where dynamic thermal-energy building simulation tools and continuous environmental monitoring are used for predicting future outdoor or indoor climate conditions in heritage structures, with the final aim of evaluating climate change induced effects on historic buildings and their surface materials [12–14]. When the indoor environment is of interest, such as in the case of museums, these analyses are typically aimed at designing suitable architectural retrofits and energy upgrades consisting in the combination of passive and active strategies [15,16], such as the application of tailored cool tiles with the same appearance of historical ones and low-impact renewable energy systems for heating and cooling. Additionally, in the case of both indoor and outdoor deterioration risks, the analysis is aimed at both preserving cultural heritage value of the building, e.g. museums, but also at guaranteeing visitors' environmental comfort conditions [17,18]. Therefore, the analysis and diagnosis of the deterioration process of historical constructions is a complex process requiring multiphysical analysis methods and compliance with rules and regulations [19,20] on conservation of architectural heritage and visitors'-occupants' comfort and safety conditions [21,22].

A major lack in most of the literature works reviewed above is that they miss the fundamental integration of thermal-energy simulation and monitoring tools with structural analysis methods, where structural conditions are also assessed and interactions between structural damages and material degradation are studied in details. That is the reason why, coupled thermal-energy analysis by means of in situ surveys and dynamic simulations are combined in this study with mechanical tests and structural investigations. The thermal-energy model in particular, after careful calibration and validation through experimental air temperature data profiles, allowed the forecast of superficial temperature profiles, representing one of the key forcings to material degradation, as coupled to humidity related phenomena. As a matter of fact, a degraded material results in a lower load bearing capacity of the whole structure that, in general, becomes more prone to failure under permanent (e.g. dead loads) or exceptional (e.g. earthquakes) loads. The overall evaluation of the health conditions of historic masonry structures is the result of a complex assessment process that requires multidisciplinary approaches [23]. The seismic vulnerability of historic masonry structures, and its reduction caused by material degradation, is a primary concern in Mediterranean countries, where recent earthquakes caused major damages to this type of buildings [24–31]. Several studies investigated damaging processes affecting historical structures, including advanced diagnostic and monitoring methods [32–38], but often missed the contribution of climate forcing, or at most considered the environmental effects only for their removal from the monitoring data [39,40]. On the contrary, a structural damage affecting masonry, typically in the form of cracks passing through mortar layers and stone or brick elements, locally results in a less protected material that is more exposed to awkward environmental conditions and, therefore, to degradation phenomena. Therefore, a closed-loop interaction between structural damage and material degradation has to be considered through a suitable and synergistic comprehensive approach, proposed in this work.

This paper proposes an integrated methodology for architectural heritage preservation, aimed at producing a hierarchical map of material degradation risk on the façades of historic masonry buildings. The local degradation risk is quantified, on a scale from 0 (low risk) to 6 (high risk), whereby the highest risk class corresponds to regions where structural damage and degradation jointly insist and are both expected to increase in the future due to climate change and repeated loadings. Lower risk levels correspond to less critical conditions, whereby, for instance, either damage or degradation are not present, or likely stable in the future. The methodology is fed by the outputs of thermodynamic and structural simulation models that, in turn, are calibrated on the basis of field monitoring data and preliminary site inspections and damage/degradation surveys.

An illustrative application of the proposed methodology is presented by taking the monumental Consoli Palace in Gubbio, Italy, as the case study benchmark. The building is especially meaningful owing to its great historic and cultural value and because it exhibits a moderate state of structural damage and different active mechanisms of materials degradation. For this reason, the building was chosen as one of the test beds of Horizon 2020 European "HERACLES" project, whose focus is enhancing resilience of historic buildings and archaeological sites against climate change related effects [41,42].

The rest of the paper is organized as follows. Section 2 presents the proposed methodological approach for hierarchical material risk degradation mapping. Section 3 presents the case study building, as well as the field surveys of material degradation and structural damage. Section 4 presents formulation and calibration of the thermo-dynamical analysis model, while Section 5 focuses on the structural analysis model. Section 6 presents the results of the application of the proposed approach to the case study, using the outputs of the models as inputs. Finally, the paper is concluded with main findings and future developments summarized in Section 7.

2. The proposed methodology

Building upon the outlined research background, the present work aims at proposing an integrated methodology for the diagnosis of climate change induced material degradation risk on the external surfaces of historic masonry structures, accounting for the existing closed-loop interaction with structural damage. The impact of past, present, and future climate conditions responsible for materials degradation, considering structural performance, is studied in details.

The proposed methodology for material degradation risk mapping is illustrated in Fig. 1. The methodology proposes a novel, integrated and replicable approach for the diagnosis of heritage constructions affected by climate change, combining experimental and numerical methods, as well as structural and thermal analyses. It starts with a knowledge acquisition phase, consisting in archival

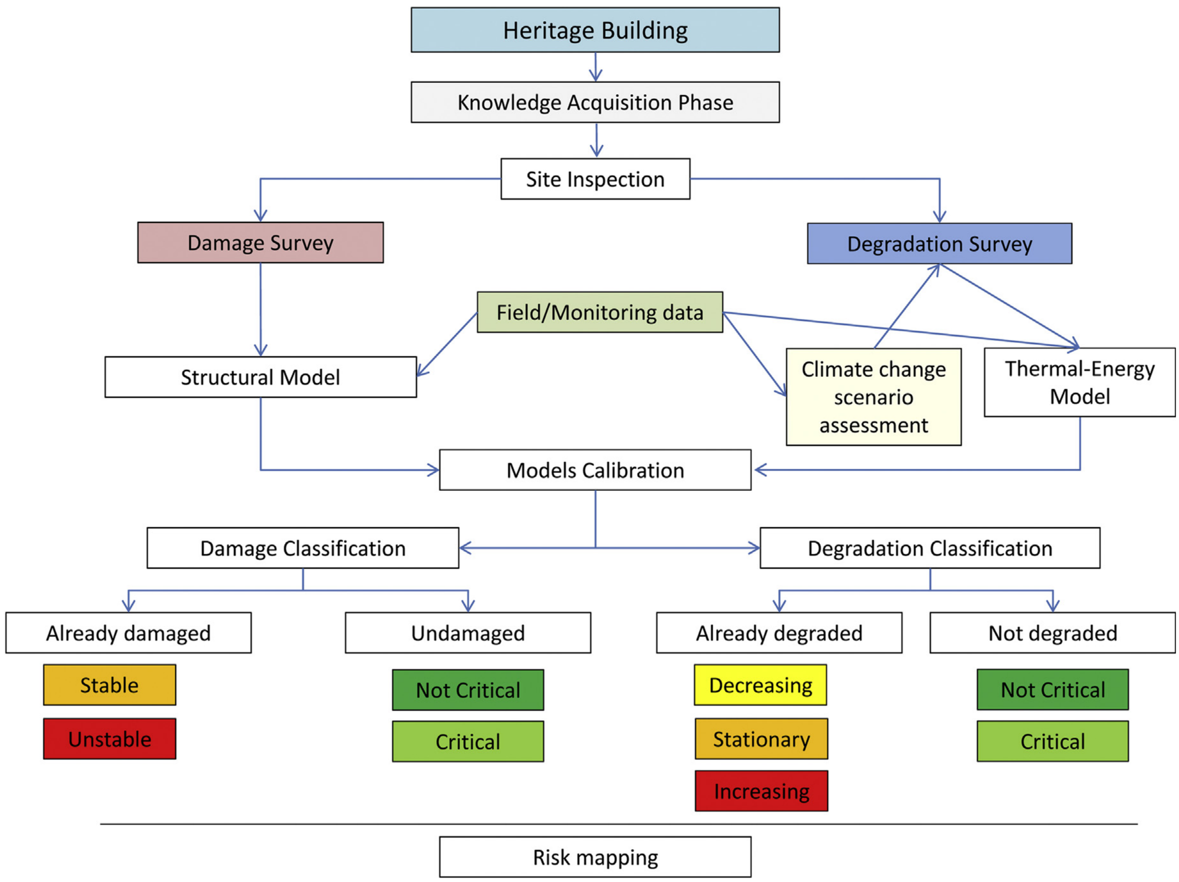

Fig. 1. Flowchart of the proposed hierarchical material degradation risk mapping methodology.

historical background analysis, as well as material and geometrical surveys in the field. Then, it continues with a site inspection and a detailed survey of structural damages and degradation phenomena. Then, structural and thermal-energy models are built, that are fed by indoor-outdoor monitoring campaigns of the main structural and environmental parameters of the heritage building for calibration purposes. Once models have been calibrated, they are run in order to classify damages and degradation phenomena. The structural model is run to evaluate the nonlinear static response under dead loads, as well as under lateral loads (pushover analysis) representing the effect of earthquakes. If needed, static analysis under settling of foundations could be also considered. Thermal-energy predictive numerical models of the building are run for identifying the current microclimate conditions in the building indoors and also by considering a variety of climate change prediction scenarios. In details, IPCC predictions are evaluated and properly selected according to global greenhouse gas emission pathways in order to elaborate past, near-term and long-term future climate scenarios (i.e. 2050 and 2080) forcing the building thermal-energy behavior and material conservation. The results of such analysis are indeed firstly used to identify causes of damages and degradation. Structural damages are classified into stable and unstable, if already existent, or critical and not critical if not yet existing. A stable structural damage is typically caused by vertical dead loads, while an unstable damage could be associated to a past seismic event or to settling of foundations associated to a climate-induced change in water content or underground water level of the subsoil. Degradation phenomena are associated to their main environmental physical drivers and classified into (i) decreasing, (ii) stationary or (iii) increasing, depending on the expected future trend of the critical environmental parameters. Based on the same future climatic outlooks, a building portion that is not yet degraded can be classified as critical if future climate predictions may suggest the occurrence of awkward conditions.

The proposed methodology consists in the evaluation on a score basis from 0 to 6, where 0 corresponds to the lowest risk class (VII) and 6 corresponds to the highest risk class (I). The highest risk is attained in those portions of the external façades that are locally affected by an active climate-driven material degradation and a potentially increasing structural damage. Following the proposed approach, summarized in Fig. 2, severity of a specific type of material local degradation is evaluated on a scale from 0 (low severity) to 3 (high severity). This number is then summed up to local severity of structural damage, also evaluated from 0 (low severity) to 3 (high severity), to get the final risk score. The evaluation first considers the presence or absence of material degradation and structural damage at initial conditions, based on detailed degradation and damage surveys carried out on the building. Afterwards, thermal analysis considering future climatic conditions is carried out to assess the outlook of materials degradation whereby different cases are considered, namely: a likely increasing degradation in the upcoming years due to more severe climate change related conditions, a likely stationary degradation, a likely decreasing degradation (if applicable), a potentially activating degradation mechanism in a region that is not degraded at the time being, or a likely stable not degraded region. Similarly, a suite of structural analyses is run to classify an existing damage into a likely stable damage (cracks due to vertical dead loads, not expected to increase in the future) and to a potentially unstable damage, that is, a dam-

	Material Degradation imputable to climate change					Structural Damage			
	Yes			No		Yes		No	
Rank	+	0	-	L	U	US	S	L	U
Points	3	2	1	1	0	3	2	1	0
I (6)	✓					✓			
II (5)	✓						✓		
		✓				✓			
III (4)	✓							✓	
		✓					✓		
			✓			✓			
				✓		✓			
IV (3)	✓								✓
					✓	✓			
		✓						✓	
			✓				✓		
				✓			✓		
V (2)		✓							✓
			✓					✓	
				✓				✓	
					✓		✓		
VI (1)			✓						✓
				✓					✓
					✓			✓	
VII (0)					✓				✓

+: increasing trend; 0: stationary trend; -: decreasing trend; L: likely; U: unlikely; US: unstable; S: stable

Fig. 2. The proposed risk class assessment method accounting for interactions between material degradation and structural damage.

age whose severity might increase in the future if events similar or stronger than those occurred in the past should take place (e.g. cracks of past earthquakes). In a similar way, structural analysis will also highlight those regions that are undamaged at the time being, but could be damaged if events similar to those occurred in the past would take place.

3. The Consoli Palace

3.1. Knowledge acquisition phase

The case study building is represented by the Consoli Palace in Gubbio, an ancient town located within the Appennine mountains of central Italy (Fig. 3). The palace belongs to a unique Medieval monumental complex, composed of two major buildings, Consoli Palace and Podestà Palace, facing the same square, named Piazza Grande, which is a slightly sloped square roof, sustained by a series of arches and vaults that raise by about 20 m from the foundation level. Consoli Palace, in largest part made of calcareous stone masonry, was built between 1332 and 1349, and since 1909 it has been used as museum space hosting a rich collection of art pieces related to the local history and culture, from the prehistory to the 20th Century. Recent restoration activities carried out in 1980 focused on the cleaning of the external façades through abrasive treatments, with no other notable intervention on the building.

The palace has two different foundation levels adapting to the slope of the Ingino Mountain. The highest point of the palace, on top of the bell-tower, reaches a total height of about 60 m with respect to the lowest foundation level (Fig. 3). The plan has an almost regular rectangular shape of about 20×40 m, whereby the internal space is articulated in several floors and internal volumes. The South façade is architecturally characterized by the Loggia, an overhanging structural volume raising up from the base up to the top of the palace. The age of construction of the Loggia could not be identified from archival researches and some authors reported that it is coeval to the rest of the palace.

In order to give an idea of the internal complexity of the palace, Fig. 3 depicts some floor plans, referring elevation quotes to the level of the external square. The lowest floor of the palace, located at a level of -7.30 m with respect to the square, is divided into four large spaces all covered by barrel vaults (Fig. 3d). From this level, a simple stone staircase allows to reach the main hall of the palace, named Arengo hall, placed at level of + 4.64 m above the square (3rd floor in Fig. 3e). The Arengo hall is basically an open space entirely covering the plan of the palace, with the only exception of the volume of the Loggia, through a majestic barrel vault with iron tie rods. During the Communal Age, Arengo hall was one of the most important political fulcra of Gubbio, hosting citizens' political meetings, while today it hosts the entrance of the museum and part of the stone collection. Between the first and the third floors, an intermediate level, internally divided into transversal vaulted spaces, is dedicated to both exhibitions and technical needs. This space is spatially organized following the pattern of external lesenes, which impose a regular architectural pitch to the openings towards the main square.

An open staircase connects the Arengo hall to the Noble floor located on the 5th floor (Fig. 3f), about 15 m higher than the Arengo hall. Between the two levels, there is a 4th level, made of some small spaces located inside the haunches of the Arengo barrel vault. The Noble floor presents several structural elements made of brickwork masonry dating back to 18th Century. These are, in particular, the two transversal walls, which divide the central

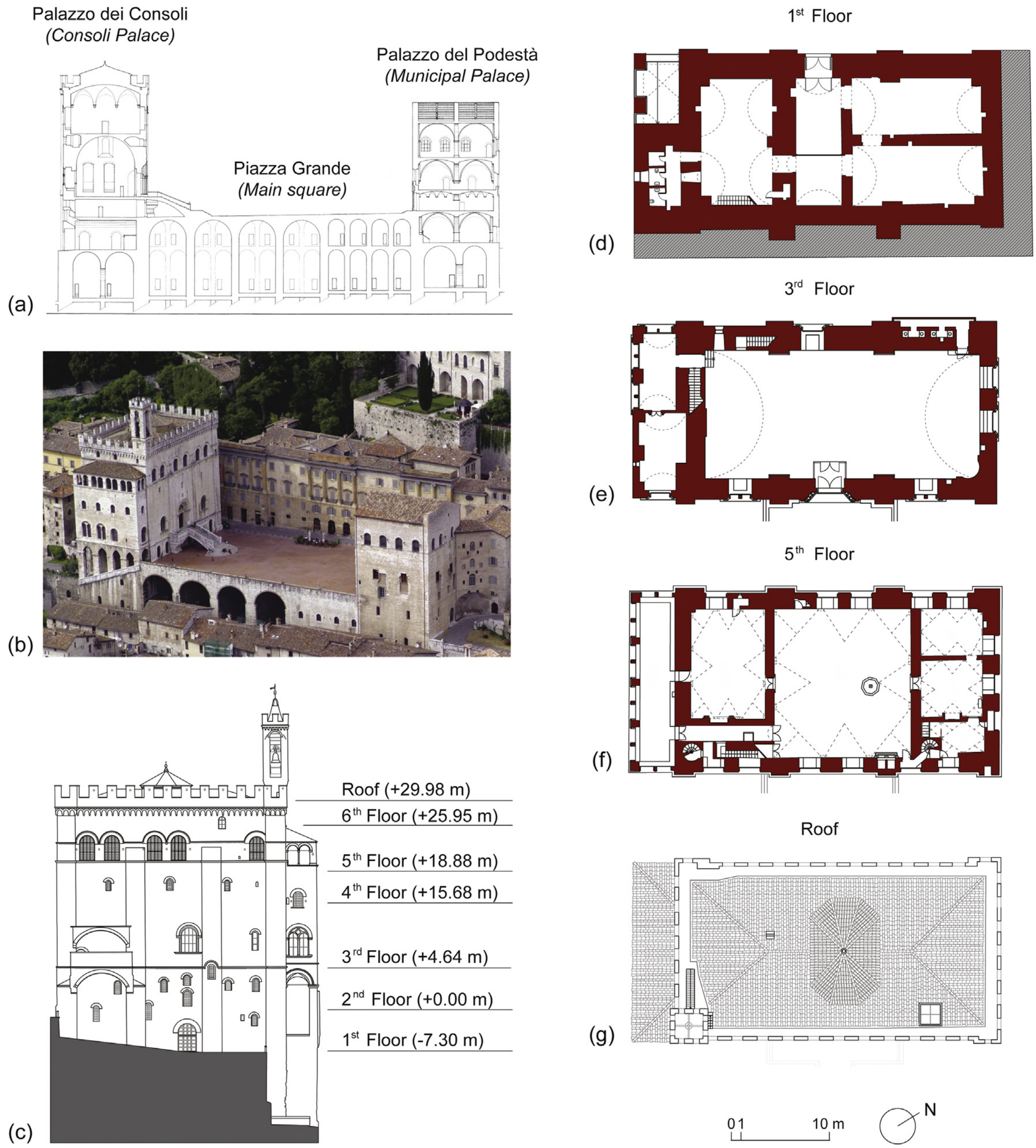

Fig. 3. Longitudinal section (a) and aerial view (b) of the Medieval monumental complex of Gubbio consisting of Consoli Palace, the Main Square and the Municipal Palace. (c) Elevation of the West façade. (d-g) Plans of the main internal floors.

Noble hall from the old private rooms of the Consuls, and the complex architectural vaults characterized by several lunettes and capitals at the skewbacks. In the southern side of the floor, the highest level of the Loggia, covered by a timber roof, is accessible.

From the Noble floor, two helicoidal stone staircases allow reaching two spaces placed over the rooms of the Consuls, at a height of about 26 m from the square level (6th floor) and the roof of the palace (Fig. 3g), from which a bell-tower stands out up to a height of about 40 m from the square. The bell-tower hosts four bells, some of which playing every 15 minutes.

3.2. Site inspections: materials degradation survey

Even if Consoli Palace is generally well conserved and continuously used as a museum space, its external façades exhibit an evident state of degradation, mainly affecting the stones. The knowledge of the type and the state of the ongoing degradations is fundamental to avoid the development of unrestrained detrimental processes affecting materials.

The causes of materials degradations must be imputed to both internal and external factors, i.e. the chemical-physical composition of the stones and their exposition to environmental actions. As far as it concerns the former aspect, the constituent material of Consoli Palace can be considered as almost homogeneous. Historical documents assess that all the calcareous stones used in the building construction were collected from quarries of the Ingino Mountain, so that the difference of inner chemical-physical properties are due to geomorphological peculiarities of the site. In this sense, the clear differences of degradation observable on the façades of the palace can be mainly related to the environmental

stresses that differently affect the various areas of the surfaces. Temperature, humidity, rainfalls, freeze–thaw cycles and pollutants are, in general, the main causes of stone degradations.

Several active degradation mechanisms were identified in various parts of the external façades of Consoli Palace. Black crust, encrustation and scaling represent the most significant states of degradation. On the contrary, biological colonization (plants and micro-organisms), the presence of localized staining due to iron elements, diffused residual discoloration after past restoration works and unsuitable reintegration of missing material (anthropic degradation) can be considered of minor significance. Following the document provided by the International Scientific Committee for Stones (ISCS) of ICOMOS (International Council of Monuments and Sites) [43] regarding the stone deterioration patterns, in the context of the physical deteriorations, black crusts and encrustations are classified as discoloration and deposit, while scaling as detachment. Black crusts are characterized by accumulation of materials on the stone surface, typically when it is protected against direct rainfall or water runoff. The peculiar chemical-physical composition of the accumulated materials, consisting of particles from the atmosphere trapped into a gypsum matrix, determines a strong adhesion to the substrate. In the case of Consoli Palace, black crusts were observed under horizontal cornices and near the moldings, which are the areas that are mostly sheltered from rainfalls. Encrustations, on the other hand, can be found on the areas of the surface where water is free to percolate. Calcareous concretions are a kind of encrustation derived by a continuous water percolation on limited portions of the surface, generating mineral outer layer of different shapes firmly adhering to the stone. The façades of Consoli Palace exhibit this kind of degradation corresponding to damaged horizontal cornices and material cracks, where water finds preferential ways to infiltrate and percolate. Differently, scaling is a degradation mainly related to physical properties and internal stresses of the material, being a detachment of stone as a scale or a stack of scales. The origin of the process can be related to the presence of microcracks developed into the stones as a consequence of mechanical and physical causes, which generate the spalling of material's portions. Among the possible environmental causes of such a degradation, freeze-thaw cycles may be mentioned. The possible interaction between structural damage and scaling is obvious and of specific interest in this work. This kind of degradation affects several areas of the façades of the Consoli Palace, resulting in local losses of materials of few centimeters in depth. Fig. 4 shows a map of the main physical degradations that were found and mapped on the East façade of the building. The existence of physical material degradation confirms the need to carry out integrated studies of structural response and material weathering, in order to analyze their possible interactions, for a better understanding of the ongoing processes and to propose suitable solutions.

The material degradation analysis also revealed the presence of biological colonization of stones by native plants and microorganisms, such as fungi and lichens. Their diffusion on the surface is mainly related to the exposition and, therefore, to local solar radiation, temperature and humidity conditions, and to the possible presence of local cavities and micro-cracks, due to erosion and mechanical stresses, respectively. Other types of degradation can be related to the use of inconsistent materials during recent works of restoration.

The evolution in time of material degradation over the main façade of the Consoli Palace is especially meaningful for the proposed methodology. Obviously, different degradation mechanisms are characterized by different velocities, depending on their causes. In order to study such a time evolution, archival pictures of the external surfaces of the building, shot in 2008, were considered and compared to pictures shot in 2016. Fig. 5 summarizes some meaningful examples of this comparison, highlighting that the physical deteriorations are much slower than the development of biological colonization. Moreover, the comparison highlights some correlations between structural damages and degradations of the materials. For example, the physical watering through stone cracks or wear mortar joints of cornices is seen to accelerate carbonation and sulfation processes of the surfaces. In this perspective, a combined diagnosis, which takes into account the damaging and degradation of materials, as proposed in the present paper, is absolutely mandatory in order to properly design the needed interventions.

3.3. Site inspections: structural damage survey

As described in Section 3.1, Consoli Palace can be regarded as a quite regular structure constituted by homogeneous masonry material, except for some internal walls and vaults placed at the 5th and 6th floors (Fig. 3). These conditions foster a regular structural behavior when the building is excited by external loads, especially by dynamic actions, such as earthquakes. In spite of the high level of seismic hazard characterizing the area of Gubbio, which results in frequent medium–high intensity earthquakes, the palace shows nowadays a moderate scenario of structural damage. In particular, some cracks appearing in a spread pattern are related to the physiological behavior of masonry material, subjected to static loads and degradation of mortar joints, and to localized shear stresses generally concentrated at the edges of the openings (windows and doors) or in the wall portions between them. On the other hand, some major cracks are compatible with two structural mechanisms: the overturning of the Loggia and of the West façade of the building.

The former mechanism mentioned above results by a combined effect due to the horizontal thrust of the vaults of the Loggia, which could explain the cracks affecting the structural elements at different levels of the Loggia, including walls and vaults, and horizontal actions. The latter mechanism is instead justified by the continuous vertical crack that raises from the ground up to the roof on the North façade of the building and that is associated with several detachment zones between the West façade and internal walls and vaults at the 5th and 6th floors. In the following developments of the paper, it will be demonstrated that the origin of this crack pattern is likely to be associated to horizontal actions and, in particular, to past earthquakes. Therefore, these cracks should be regarded as potentially unstable according to the proposed methodology, because new and stronger earthquakes might increase their criticality. Fig. 6 shows the main cracks characterizing the East and North façades of the building and the two corresponding local failure mechanisms that can be possibly activated.

4. Dynamic thermal-energy modeling

Thermal-energy modeling of the case study building was performed with the purpose of assessing both indoor and superficial thermal behavior of building materials and thermal zones, and to correlate these results with the field degradation analysis and the structural investigation. According to the proposed methodology, the model was calibrated and validated thanks to an experimental campaign implemented within the building and in the outdoor area. The following subsections illustrate these specific phases.

4.1. Experimental monitoring for models' calibration

In order to perform the calibration and validation of the numerical models elaborated for the heritage building selected as case study, a continuous monitoring of the indoor air temperature was carried out during fall 2016. To this aim, a dedicated

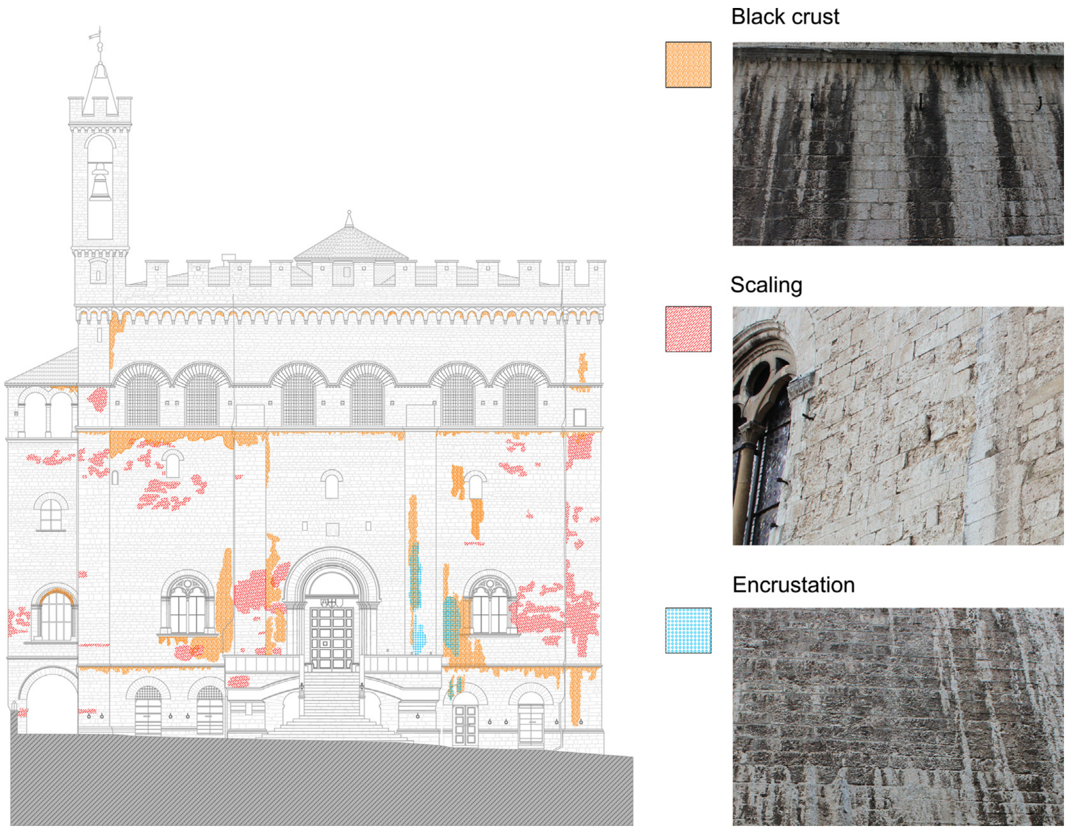

Fig. 4. Map of the main material degradations identified on the East façade of the Consoli Palace: black crust, scaling and encrustation.

datalogger-incorporated sensor [44] able to continuously collect such data with a frequency of 1 record every 10 minutes was positioned inside the Arengo hall (3rd floor in Fig. 3).

4.2. Generation of past, present and future climate boundary conditions

In order to assess the thermal-energy performance of the case study heritage building with varying climate boundary conditions, four different weather files were elaborated. Such weather files were developed within Meteonorm environment [45] to be representative of the past, current, and future expected climate conditions in the case study location. Meteonorm is a comprehensive climatological database where TMYs (Typical Metetorological Year) are stochastically generated for a given location from interpolated long term monthly average values. They represent an average year of the selected climatological time period. The model can potentially generate a weather file for every location based on the available weather parameters for the last decades of 20th Century or the first decade of 21st Century. Moreover, the same tool is meant to be able to generate future climate scenarios for every location based on IPCC's predictions [1] on climate change, which is of interest for this research. The Meteonorm protocol includes three different climate change scenarios: B1 (low emissions), A1B (average emissions), and A2 (high emissions). For the purpose of this work, a slow technology change scenario, i.e. A2, was considered also for being the most representative of the climate progress in the last decade. Therefore, the following weather files were elaborated, for the case study location:

- "Past": developed by considering data of the period 1961–1990 for air temperature and 1981–1990 for global solar radiation (this specific time was selected since the palace was subject to a cleaning intervention in the '80 of last century as key staring point of the current degradation state due to pollution crusts and other mechanisms, as previously observed);
- "Current": developed by considering data of years 2000–2009 for air temperature and 1991–2010 for global solar radiation;
- "Future 2050": developed by taking into account the predictions for year 2050 of IPCC's A2 scenario;
- "Future 2080": developed by taking into account the predictions for year 2080 of IPCC's A2 scenario.

4.3. Elaboration of the building dynamic thermal-energy model

After the elaboration of the model (Fig. 7), the simulation of the current, the past, and two different future climate scenarios were carried out within the internationally acknowledged DesignBuilder-EnergyPlus dynamic simulation environment. The implemented model allowed to perform the dynamic calculation every 10 minutes of the heat balance-based solution of radiant and convective flows responsible for the generation of surface temperatures profiles, indoor thermal comfort and condensation within the envelope elements. Therefore, four different simulations were performed with varying weather file, i.e. "Past", "Current", "Future 2050", and "Future 2080" [46] as significant environmental boundary conditions describing the climate change progress in the next decades, as specified in Section 4.2. The modelling procedure started with the field inspection conducted in parallel with the architectural and structural survey campaigns. Materials analysis, geometric parameters and building occupant behavior and operations were identified as key thermal parameters and periodical profiles.

The model was indeed elaborated by taking into account the real characteristics of the Consoli Palace in terms of construction techniques, occupancy levels, indoor activities, internal gains and

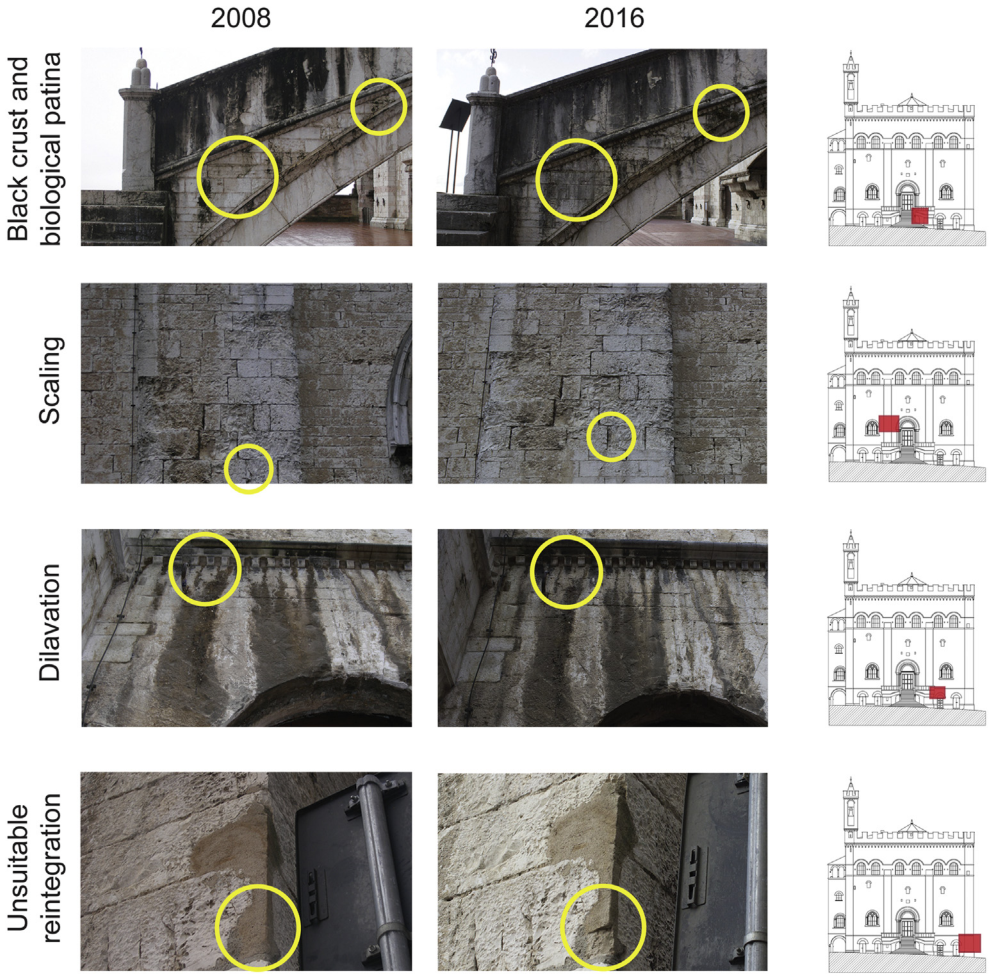

Fig. 5. Time evolution of the main material degradation processes observed on the East façade of Consoli Palace: comparison between 2008 and 2016.

thermal zones, as summarized in Table 1. Constituting materials mainly consisted in calcareous stones characterized by a thermal conductivity of 2.210 W/mK, a specific heat of 840 J/kgK, and a density of 2550 kg/m^3.

The simulations were carried out both in free-floating and in controlled conditions by active systems. The free floating conditions were aimed to determine the indoor behavior of thermal zones and the superficial thermal profiles of envelope materials affecting the progress of degradation phenomena, assuming the building itself as subject to outdoor weather conditions identified as specified before, i.e. climate change site specific weather file. The controlled conditions were aimed to simulate the behavior of the overall building and of its thermal zones while energy systems were meant to be operating, therefore by assuming the full occupancy behavior as a museum and a public space, as it is the case in the palace. This second analysis allowed to assess the energy behavior of the palace and its variability due to climate change action, i.e. the potential increase in cooling needs and decrease in heating needs, and the indoor thermal comfort conditions for visitors and daily employees.

In the case of the performed controlled simulations, the set point temperature was set equal to 20 °C and 24 °C for winter and summer, respectively, according to the real setup of the building systems identified in the field. The main purpose of this set of simulations was also to assess the surface temperature of the building materials to correlate the field observation about the degradation state with thermal-dependent degradation phenomena in the past, present, and future climate conditions. However, for calibration purposes, aspects such as indoor thermal comfort conditions and overall building performance in terms of primary energy requirement were also considered. Table 1 reports the most significant operation setups of the thermal zones in terms of daily agenda and percentage of functionality of the four identified thermal zones, i.e. public areas, storage rooms, laboratory and main hall. Internal thermal power gains due to the field activities were assumed while performing the real survey during the course of the time, as again reported in Table 1.

4.4. Validation of the model

Validation of the model was carried out by using experimental data in terms of air temperature, as monitored in the building, as previously mentioned. Air temperature measured profiles were collected and compared to the simulated ones in the palace main hall. To this end, the measured and the simulated air temperature values were then compared in terms of mean bias error (MBE) and root mean square error (RMSE), as reported in the ASHRAE Guidelines 14 [47]. The calculated values corresponded to 0.33 and 1.07 for the MBE and RMSE, respectively, which comply with the thresholds suggested in [47] for validation. Overall, the model can be therefore considered as representative of the realistic thermal behavior and indoor conditions of the case study building [47].

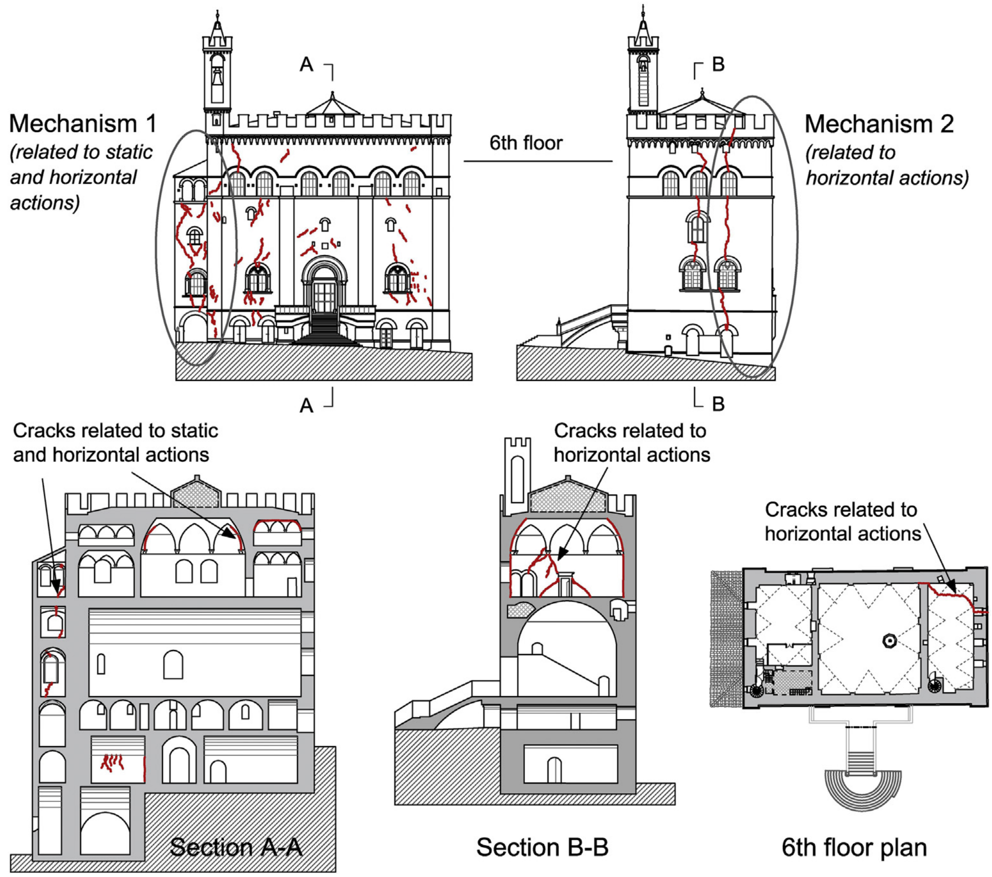

Fig. 6. Survey of structural cracks on the East and North façades of the Consoli Palace, highlighting the two possibly activating local failure mechanisms by plan and internal sections views.

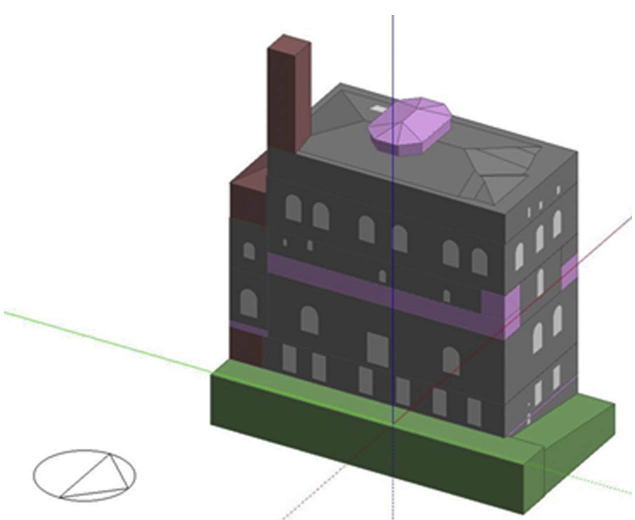

Fig. 7. Graphical scheme of the building for the thermal-energy dynamic simulation analysis.

5. Numerical FE modelling and model tuning

A numerical model of the case study building was built in order to evaluate its structural conditions and classify existing cracks into stable (due to dead loads) and potentially unstable (due to earthquakes) ones, as well as to identify regions where new cracks may develop as a consequence of seismic events.

On the basis of the geometrical and architectural surveys described in Section 3.1, a 3D Finite Element (FE) model was developed using tetrahedral elements, which are especially suited to discretize irregular volumes (Fig. 8). As far as it concerns the boundary conditions, at the bases of the building all degrees of freedom were fixed, while on the vertical sides in contact with the soil only the lateral displacement was fixed. By a visual inspection, the structural constituent material can be considered as basically homogeneous, except for some vaults and internal partition walls of the Noble floor. Nevertheless, given the negligible difference in terms of mass and stiffness contribution with respect to the overall behavior of the structure, the material was considered as homogeneous and isotropic. The values of mass density and Young's modulus were taken from the Italian technical standard [48] as a first attempt. According to the proposed methodology, the model was calibrated and validated on the basis of an experimental campaign, in the present case consisting in Ambient Vibration Tests (AVTs) and sonic tests, as illustrated more in detail in [42].

AVT is a fully non-invasive experimental test aiming at investigating the global dynamic behavior of a structure, by using its dynamic response output to an unmeasured dynamic input, using vibration sensors such as accelerometers. The achievable dynamic characteristics are natural frequencies, mode shapes and damping ratios, that are quite useful for a finite element model calibration, at least in terms of equivalent elastic material properties.

The dynamic characteristics of Consoli Palace were investigated during an AVT carried out on May 4th 2017, using 9 uni-axial high sensitivity piezoelectric accelerometers (model PCB 393B12, 10 V/g) arranged on the three main floors of the palace, as shown in

Table 1
Main thermal zones assumed in the building model and relative assumptions.

Activity	Display and public areas	Store room	Laboratory	Hall/lecture theatre
Occupancy schedule	07:00–08:00, 25% 08:00–09:00, 50% 09:00–12:00, 100% 12:00–14:00, 75% 14:00–17:00, 100% 17:00–18:00, 50% 18:00–19:00, 25%	09:00–17:00, 100%	07:00–08:00, 25% 08:00–09:00, 50% 09:00–12:00, 100% 12:00–14:00, 75% 14:00–17:00, 100% 17:00–18:00, 50% 18:00–19:00, 25%	09:00–17:00, 100%
Internal gains (occupancy)	0.15 persons/m^2	0.12 persons/m^2	0.10 persons/m^2	0.15 persons/m^2
Internal gains (equipment)	3.5 W/m^2	–	11.0 W/m^2	1.5 W/m^2

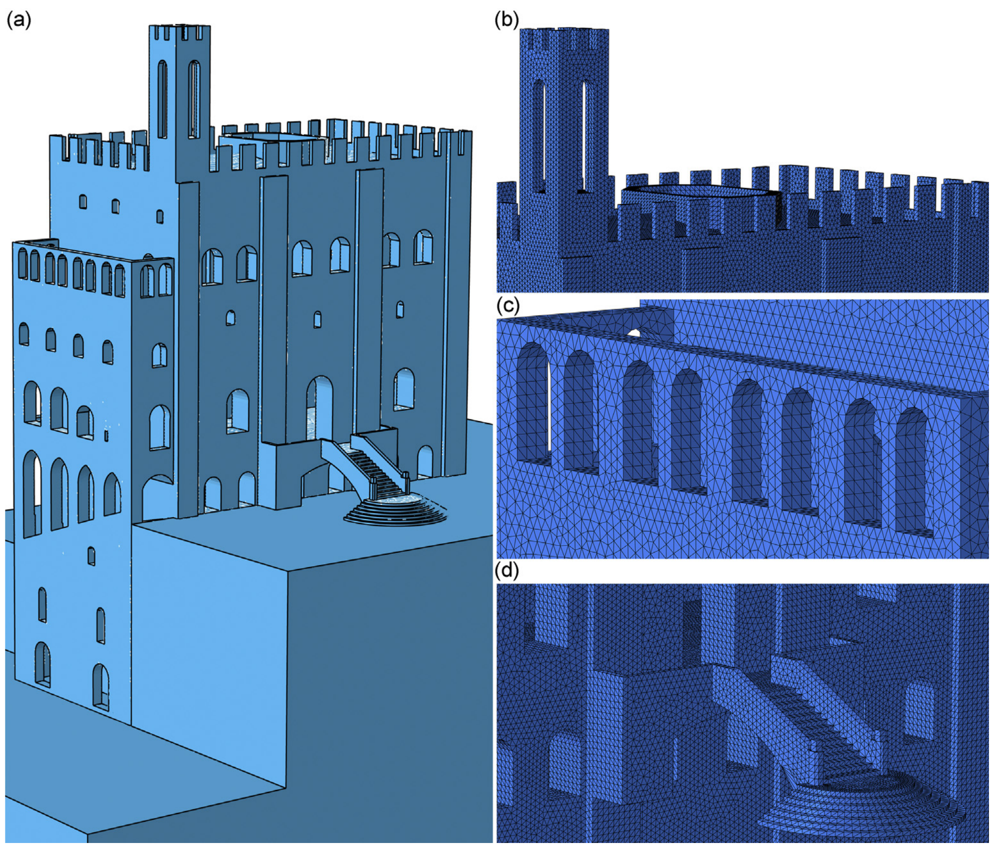

Fig. 8. (a) Solid 3D model of the Consoli Palace including portion of the surrounding soil. (b-d) Zoom sketches of the meshed Finite Element Model.

Fig. 9a, in order to estimate the mode shapes with a reasonably accurate spatial resolution. In all the instrumented floors, sensors were deployed with a configuration apt to measure rigid diaphragm motions in two orthogonal directions, as well as torsional rotations. Several configuration setups were considered in the top part of the building in order to account for the expected plane deformability of building floors. For this reason, sensors were deployed both close to the short façade of the palace on the side of the Loggia, thus minimizing the length of wired connections and measuring the motion of the building on its highest side, and close to the main façade of the palace, maximizing the distance between the parallel sensors for better describing global torsional motions. The tests were conducted in operational conditions, by considering micro-tremors, mainly due to wind and to weak vehicle traffic actions, as source of dynamic excitation. The sensors were connected to a multi-channel acquisition system (24-bit resolution, 102 dB dynamic range and anti-aliasing filters) and data were collected in separate 30-minutes long files, corresponding to more than 4000 times the fundamental period of the building. The acceleration data were recorded, after down-sampling, with a sampling frequency of 40 Hz.

Before data processing, a pre-processing procedure was implemented, in order to remove anomalies (e.g. spikes) and non-stationary excitation effects produced by the tolling of bells, placed in the bell-tower of the palace, which play with a 15-minutes regularity all day and night long. The structural modal parameters were extracted by means of two different tools: the classic Frequency Domain Decomposition (Fig. 9b), in its standard (FDD) and enhanced (EFDD) versions [49], implemented in the commercial ARTeMIS [50] software, and the Stochastic Subspace Identification (SSI) technique developed by the authors in a previous work [51].

The analysis performed in the frequency domain allowed to identify six modes of vibration, as reported in the singular value plot of Fig. 9b. Three modes involve the overall building, being two global flexural modes, in x and y directions, respectively (modes Fx1 and Fy1), and one torsional mode (mode T1), while the remaining three modes consist in mixed and/or local modes

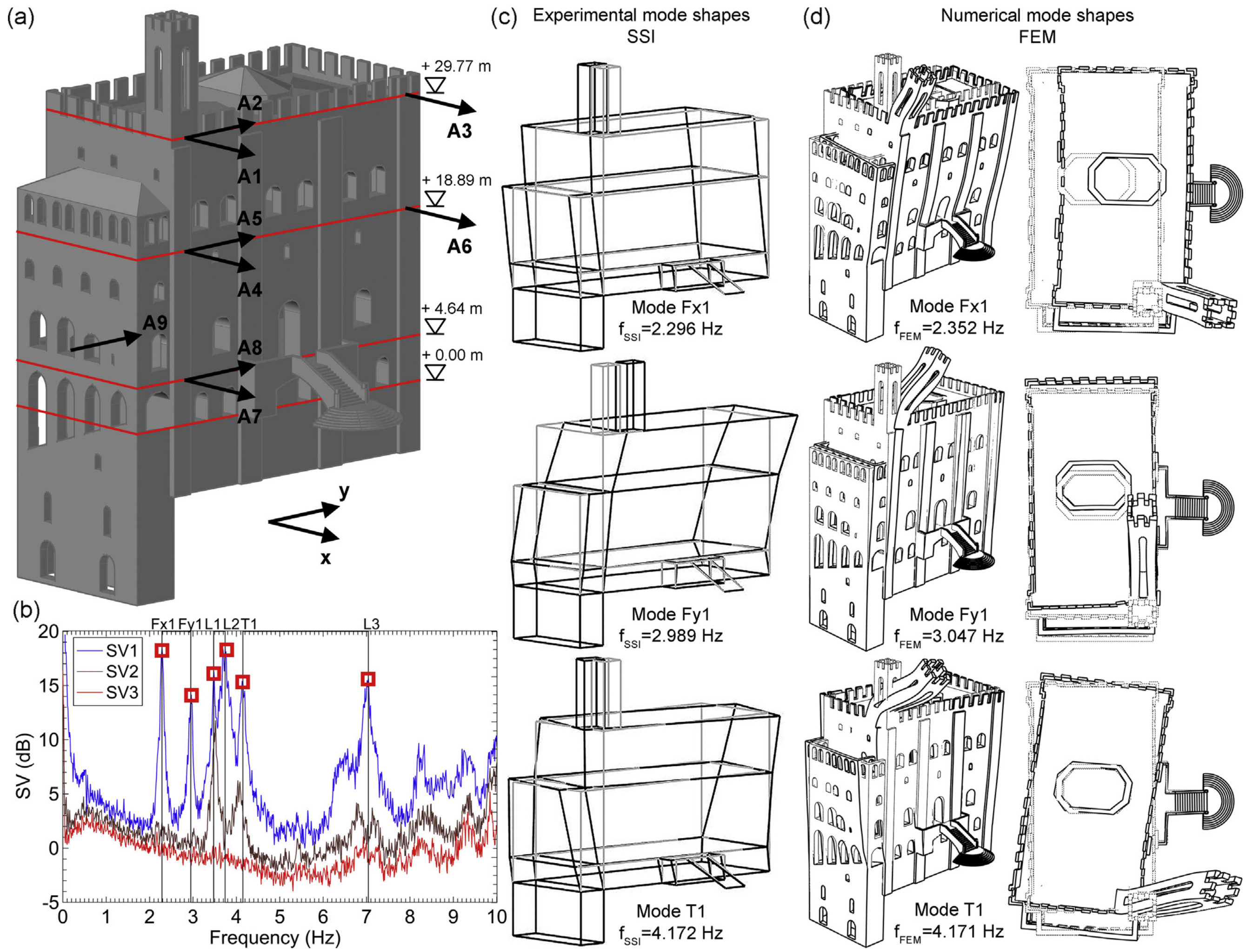

Fig. 9. AVT of May 4th 2017: accelerometers layout on the three main floors of the palace (a) and first three Singular Values of spectral matrix by Frequency Domain Decomposition (b). Experimental (Stochastic Subspace Identification) and numerical (Finite Element Model) global mode shapes of Consoli Palace (c-d).

related to the dynamic interaction between the palace and the bell-tower (modes L1, L2 and L3). A consistent interpretation of these last modes was elaborated through the modal analysis obtained by the numerical model confirming the global nature of modes Fx1, Fy1 and T1, and the local nature of the remaining modes, mostly affecting the bell-tower but also producing slight but measurable movements on top of the building [42]. Similar experimental results were also obtained using the SSI technique. Table 2 summarizes the structural dynamic properties, in terms of natural frequencies and damping ratios, as obtained by application of both procedures.

The model calibration was essentially carried out through a manual tuning procedure, starting from the results given by in-situ sonic tests and a numerical sensitivity analysis, aimed at searching for an optimum match between numerically predicted and experimentally identified natural frequencies of the global modes of vibration (Table 3). It was necessary to refer to an isotropic elastic model in order to use a specific damage model in the nonlinear analysis as better described in the following. As shown in [42], after manual tuning, the average error between identified and predicted natural frequencies resulted equal to 1.452%, which indicates a very good agreement, even though the analysis is necessarily limited to the only three global modes that were identified from the AVT (Table 4). The deviation from the mixed and local modes is probably due to the necessity of an improvement in the modelling of the bell-tower, which requires a more in-depth investigation and can be considered out of scope for this paper. The comparison between the experimental and numerical mode

Table 2
Identified vibration modes of Consoli Palace using different identification techniques.

Mode no.	Mode type	f_{FDD} (Hz)	f_{EFDD} (Hz)	f_{SSI} (Hz)	ξ_{EFDD} (%)	ξ_{SSI} (%)
1	Fx1	2.305	2.297	2.296	1.135	1.121
2	Fy1	2.979	2.985	2.989	0.999	0.751
3	L1	3.496	3.510	3.508	0.784	0.779
4	L2	3.721	3.741	3.743	1.726	2.477
5	T1	4.170	4.172	4.172	1.431	1.104
6	L3	7.041	7.022	7.035	0.819	1.089

Table 3
Parameters assumed in the FE numerical model after calibration.

Structural part	E [MPa]	ν	ρ[t/m^3]
Gattapone level	3327	0.34	1.90
Arengo level	3510	0.34	1.90
Noble level	3327	0.34	1.90
Bell-tower	3450	0.34	1.90

shapes is represented in Figs . 9c and 9d in which a good agreement can be observed for global modes Fx1, Fx2 and T1.

The nonlinear constitutive behavior of the material was described through the Concrete Damage Plasticity model [52], as suggested in relevant literature works [53–57], considering the mechanical values suggested by the Italian technical standard code for limestone masonry with good arrangement of blocks [48]. These values correspond to a compressive strength σ_c = 3.5 MPa and to a tensile strength σ_t = 0.3 MPa; the nonlinear behavior of the material was described through a bi-linear path, i.e. with an elastic perfectly plastic material, both in tension and compression, as suggested by the Italian guidelines for the assessment of historical monuments in the case of nonlinear static analysis [58]. The choice of this material behavior allowed to identify the weakest structural parts, classifying stable and unstable cracks, as well as critical and not critical regions in terms of cracking as required by the proposed procedure, without aiming at a precise assessment of structural vulnerability. In this way, it was not necessary to introduce additional numerical damping, such as the viscosity parameter implemented for the viscoplastic regularization of the Concrete Damage Plasticity model.

6. Interpretation of the degradation state and construction of the risk map

6.1. Building thermal-energy behavior within different climate scenarios

This section presents the results of the dynamic building simulations performed in free-floating conditions for the different climate scenarios, i.e. past, current, future 2050, and future 2080. In particular, Figs. 10 and 11 show the indoor operative temperature trend during the typical winter and summer week, respectively. Both the summer and winter results show a progressive increase of the indoor operative temperature during the years, from the past climate scenario to the future, i.e. up to 2050 and 2080. Such a trend is directly imputable to the near-term global warming phenomenon foreseen for the next decades as stated by the IPCC 4th assessment report (scenario A2). More in details, an average overheating up to 2 °C is detected by comparing the current and future (i.e. 2080) climate scenarios, while a slightly lower overheating, i.e. up to a maximum of 0.5 °C, is registered between the current and the future 2050 climate conditions. As expected, in the past weather file, the indoor temperature is always lower than in all other climate scenarios. The maximum indoor operative temperature difference is detected between the past and future 2080 configurations and it corresponds to 2.5 °C.

About the summer results, the free-floating dynamic simulation shows up to a 2.5 °C temperature increase by switching from the current climate scenario to the future 2080 boundary conditions. Moreover, consistently with the winter results, a slightly lower but constant temperature increase, i.e. up to a maximum difference of 0.5 °C, is registered by comparing the current climate conditions with the near future scenario at 2050. Again, as in the winter analysis, lower temperature values are consistently detected for the past climate scenario compared to all other cases, with a maximum difference of 4 °C between the past and future 2080 climate scenario.

6.2. Materials degradation and pathologies in different climate scenarios

In order to assess the trend of material degradation over time, the correlation with to local microclimate phenomena was evaluated. The historical weather data collected by local meteorological stations were firstly analyzed in order to identify the trends over time of the microclimate parameters mainly due to local climate phenomena such as extreme rain events. In this view, the data series related to the rainfall and relative humidity were selected. Secondly, such trends were correlated to the external surface temperatures of the construction materials of the selected case study in order to understand possible deterioration phenomena directly imputable to such local microclimate conditions. Fig. 12 shows the trends of the measured microclimate parameters in terms of rainfall and relative humidity from 1989 and from 2008 up to today (left) and the trends of the simulated construction surface temperature (right).

The diagrams in Fig. 12 allow the identification of local microclimate trends consisting of the increase of extreme rainfall events and ambient relative humidity over the years (i.e. from 1989 to 2015). Figs. 12a and 12b report the annual value of rainfall, Fig. 12c reports the simulated trend of annual relative humidity which may exacerbate water related degradation phenomena, together with rainfall intensity increase. Fig. 12d reports the monthly average values of external surface temperature on the North oriented and the East oriented façades of the palace, affecting water condensation phenomena, in the past and currently. Fig. 12e reports the same trends with also the comparison to future climate scenarios. Finally, Fig. 12f reports the hourly profile of external surface temperatures in the critical winter day in the past, currently, on 2050 and 2080. As a matter of fact, the following main phenomena directly attributable to the peculiar local microclimate trends can be identified [59]:

- despite of the increasing trend of temperature, the scaling phenomenon of the stones of the façade is going to likely increase mainly due to the rainfall effect;
- the increasing trend of rainfall is exacerbating the ongoing processes of percolation and incrustation locally identified on the palace;
- the growth of organic materials, moulds, vegetations, and crusts over the façades surface will likely increase.

Table 4
Comparison between experimentally identified (f_{ID}) and numerically predicted natural frequencies (f_{FEM}): Δf represents the relative difference (Δf_{mean} the mean relative difference) and MAC the Modal Assurance Criterion values for each mode.

Mode	f_{ID} (Hz)	f_{FEM} (Hz)	Δf (%)	MAC	Experimental		
Fx1	2.296	2.352	2.439	Numerical	0.988	0.019	0.022
Fy1	2.989	3.047	1.940		0.002	0.737	0.156
T1	4.172	4.171	0.024		0.000	0.004	0.967
			Δf_{mean} = 1.452				

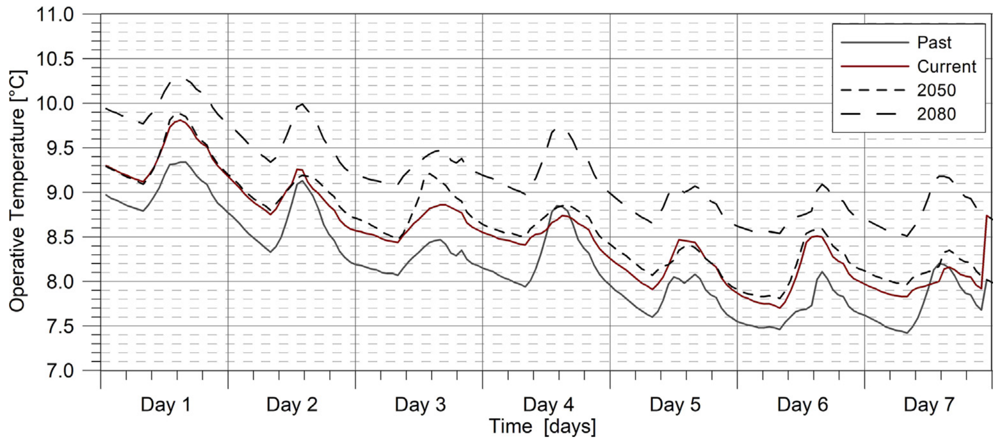

Fig. 10. Trend of daily operative temperature in the considered different scenarios during the coldest winter week.

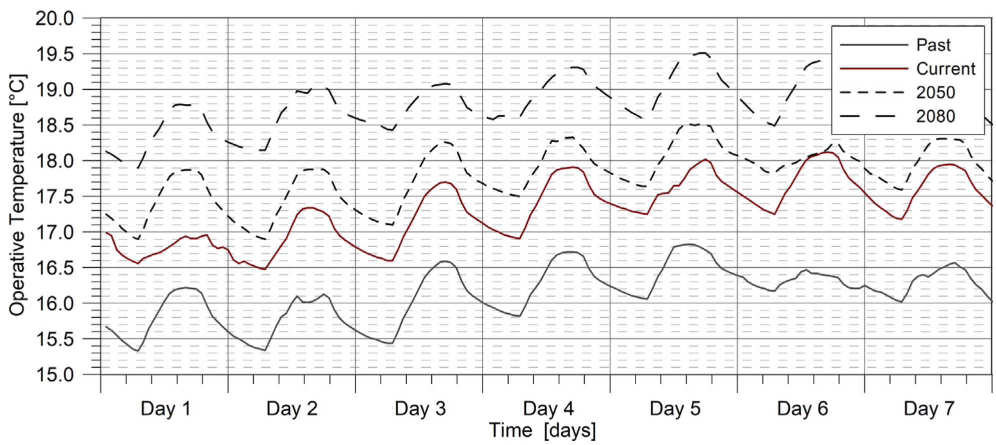

Fig. 11. Trend of daily operative temperature in the considered different scenarios during the hottest summer week.

The above observations allow to obtain a risk map of the degradation, according to the ranking level defined as material weathering consequence in Section 2. Taking into account the main purpose of the paper, which is focused on the combined effect assessment of material and structural degradations, in the following analysis, only the risk map of scaling on the main façade of the building is illustrated, which is the most interesting example for applying the proposed procedure. In particular, two regions of the façade have been identified: the area where the degradation already insists and the area where it does not appear. These regions were regularized by taking into account the structural and/or architectural macro-elements, such as main walls, lesenes, etc. On the basis of the results presented above, the driving environmental actions were assumed to have an increasing trend in the areas where the degradation is observed. From these considerations, the risk map illustrated in Fig. 13 was obtained.

6.3. Interpretation of structural degradation through nonlinear analysis

The presence of a moderate damage pattern, with major structural cracks, on the Consoli Palace could be attributed to two main causes, which may affect the structural stability of the building: static actions, such as vaults horizontal thrusts or differential settlements of foundations, possibly due to soil settlements occurred during the decades and caused by climate change related effects (heavy rainfalls and drought periods), and dynamic actions related to past earthquakes, that stroke the city of Gubbio several times during the centuries. On the other hand, spread cracking scenarios observed on the façades of the building could be related to a combined action of both the stress levels developing inside the material and the degradation of the mortar joints between stones, mainly due to environmental actions.

With the purpose of attaining a more reliable interpretation of the observed damage and crack pattern, nonlinear static analyses [60–62] were carried out by means of the previously described FE model. Pushover analyses with incremental horizontal force systems modelled according to the first two mode shapes, Fx1 and Fy1, were performed, in both positive and negative directions. The analyses were carried out in quasi-static conditions by using a force-controlled algorithm. No specific constraints were applied on the floors, being the structure modelled considering the actual geometry also in the internal walls and vaults.

As an example, Fig. 14 shows the nonlinear equilibrium path (displacement of the indicated control point vs. base shear force of the structure) obtained by the pushover analysis with a system of horizontal forces proportional to the displacement field of the Fx1 mode shape, in positive direction. The images reported inside the graph show the increasing level of the structural damage in terms of map of the plastic regions developed in the model (highlighted regions).

Fig. 15 summarizes the results of nonlinear analyses, depicting a map of the predicted damage pattern of the East façade for each case. More in detail, the spread cracking pattern observed on the

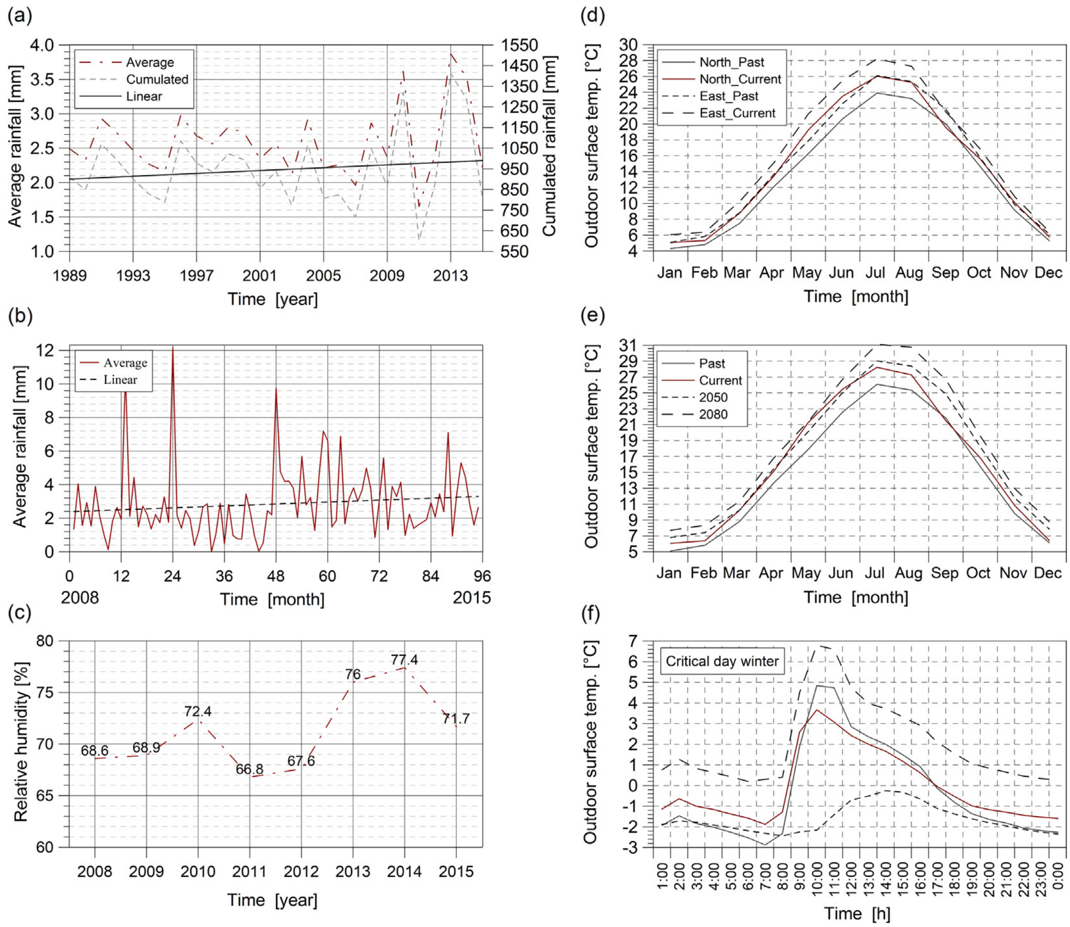

Fig. 12. Main environmental forcing trends (a-c) and related external surface temperature daily profiles with varying climate change boundary conditions (d-f).

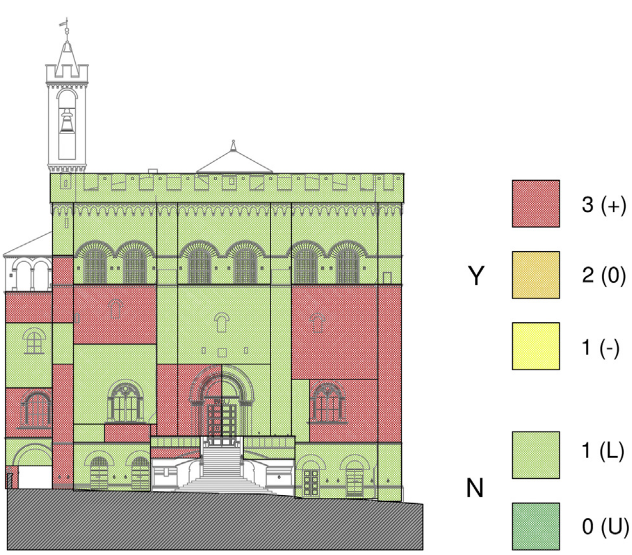

Fig. 13. Risk map of scaling degradation on the main façade of the Consoli Palace.

main façade of the palace can be imputed to the effects of multi-directional horizontal loads, while the cracks of the loggia can be related to a combined effect of the static actions (horizontal thrust of the vaults which determines a cracking scenario not visible in Fig. 15) and the seismic loads on the y direction (Figs. 15c and 15d). Making a sketch of the transversal sections, also the detachment between the external stone walls (East and West façades) and the internal brickwork walls were obtained, including the shear cracks of the transversal walls themselves (Fig. 15b).

The shear damages obtained by the pushover analyses are compatible with the crack pattern observed in the structure. In particular, there is a good correspondence between some cracks predicted by the numerical analysis and those actually detected on the building, while other numerically predicted cracks are not yet observed on the structure, likely because past earthquakes did not reach a sufficient intensity to cause such damages. However, a possible earthquake-induced cracking in these areas has to be accounted, according to the proposed methodology.

On the basis of the damage surveys and of the numerical results, the risk map of the structural degradation was constructed through the proposed methodology and according to the ranking level defined in Fig. 1. Generally, the cracks related to static loads could be classified as stable, while those related to earthquakes as potentially unstable, due to the random nature of the seismic events and the difficulty to a priori evaluate the horizontal load bearing capacity level of the building. Fig. 16 depicts the structural damage risk map derived from the above considerations.

6.4. Combined risk map for scaling degradation

The sum of the scores assigned to different portions of the main façade of the Consoli Palace in Fig. 13, for stone scaling, and in Fig. 16 for structural damages, provided the final hierarchical risk mapping elaborated by the proposed procedure, considering interaction between climate change and structural damage. The result is presented in Fig. 17 and highlights that the scenario is quite

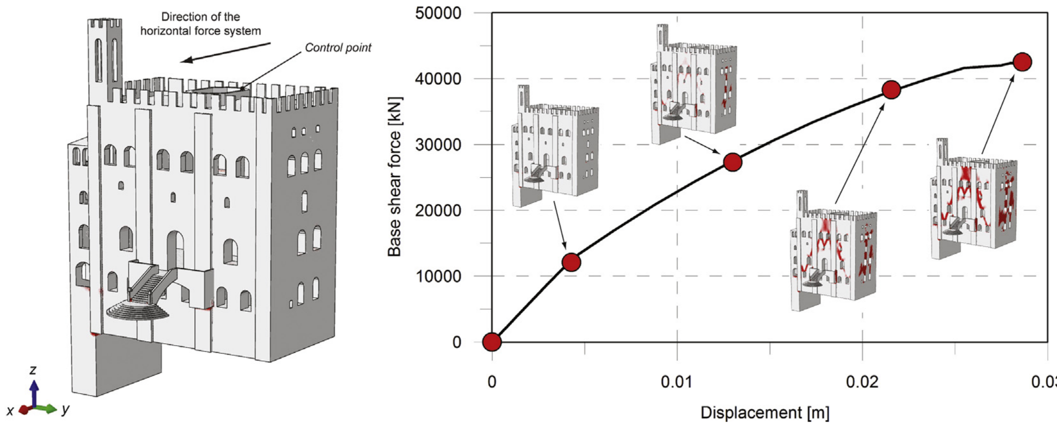

Fig. 14. Pushover curve considering a system of horizontal forces proportional to Fx1 mode shape, in positive x direction.

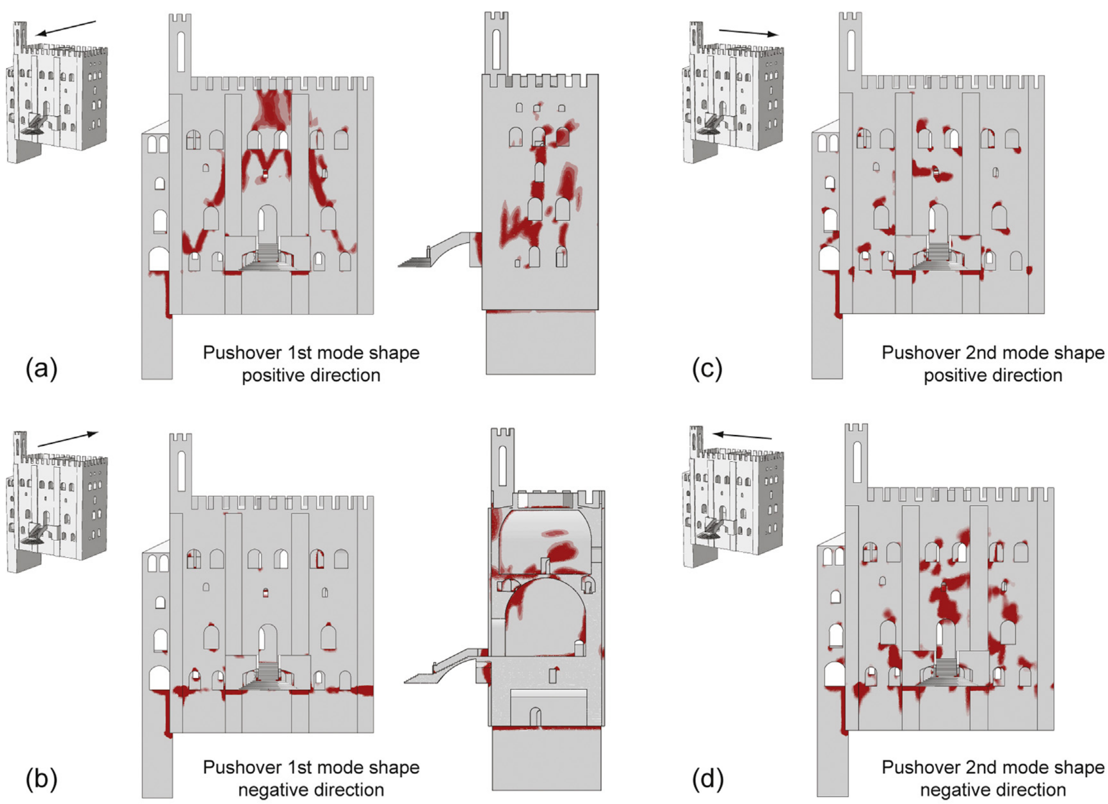

Fig. 15. Damage maps (highlighted regions) of the East façade resulting by static nonlinear analyses, with horizontal loads considered by means of a distribution of lateral loads along the x positive (a) and negative (b) direction with the shape of mode Fx1, and along the y positive (c) and negative (d) direction with the shape of mode Fy1.

heterogeneous, showing that some regions are more critical than others in terms of scaling degradation and its possible evolution in the future. Although the proposed ranking does not provide a quantitative assessment of risk, and that the same risk is not inversely proportional to the class, still this ranking can be quite useful to prioritize those regions requiring a relatively more urgent intervention with the final purpose to optimally allocate available budgets for restoration, by differentiating the restoration priority according to the classes attributable to different regions of the façade.

7. Conclusions

In the present work, an innovative integrated methodology was proposed for mapping climate change-induced material degradation risks on the external façades of historic masonry buildings, accounting for the existing closed-loop interaction between structural damage (e.g. cracks caused by vertical loads or exceptional events, such as earthquakes) and typical degradation mechanisms of stones and mortars, potentially exacerbated by climate change related events and progressive trends. As an illustrative application, the proposed methodology was applied to the pilot case study of the monumental Consoli Palace, located in Gubbio, in Central Italy, with specific focus on scaling degradation of stones on its main façade.

The proposed approach is based on a novel numerical ranking of the risk of material degradation based on a dedicated field survey of the current damage and degradation conditions, as well as on the outputs of site investigations and numerical simulations, considering both structural and environmental aspects. Field tests,

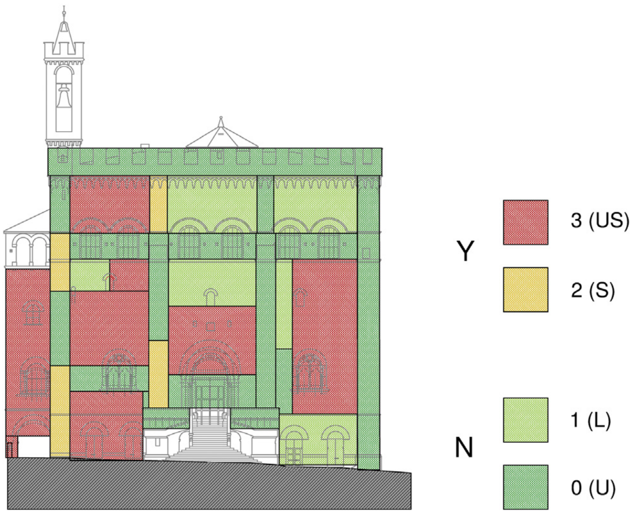

Fig. 16. Risk map of structural damages on the main façade of Consoli Palace.

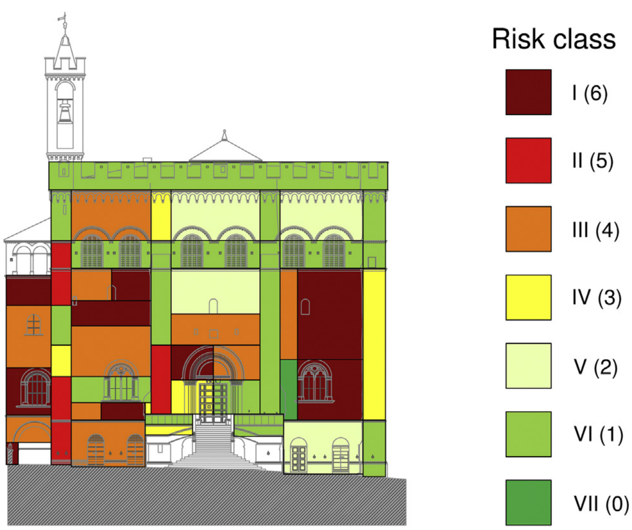

Fig. 17. Final risk map of scaling stone degradation on the main façade of Consoli Palace considering interaction between climate change and structural damage.

such as indoor-outdoor microclimate monitoring campaigns and ambient vibration tests, were carried out in order to provide information for optimal tuning of thermal-energy and structural simulation models of the building, respectively. The structural model was used to interpret the current structural damage scenario with the purpose to identify stable and potentially unstable cracks, as well as to identify critical regions where a structural damage may occur as a consequence of future exceptional events, such as earthquakes. The thermal energy model, on the other side, was used to identify critical regions that are particularly vulnerable to material degradation due to climate change according to future climate prediction models. Examples of such regions are those characterized by increasing peak summer temperature, differential thermal behavior and/or humidity with possible risk of dangerous condensation phenomena. In particular, the generation of different weather files as boundary conditions allowed to predict the progress of the identified risks compared to the past and present situation. Considered scenarios consisted in recent past (i.e. temperature progress from 1961-1990), current time (i.e. temperatures from 2000-2010) and future climate conditions based on the forecast of the latest IPCC, assuming the A2 scenario for generating the years 2050 and 2080. For the purposes of the proposed procedure, which is aimed at providing a relatively simple tool to map the most critical regions over large façades, structural and thermal-energy analysis were treated as uncoupled. However, given that temperature and moisture conditions affect material degradation and structural performance, more complex coupled models could also be adopted, when a quantitative assessment of future structural performance is needed accounting for changes in environmental boundary conditions.

As the final output of the analysis, the application of the proposed methodology to the case of the Consoli Palace resulted in a hierarchical map of scaling degradation severity over its main façade, accounting for its interaction with structural cracking and their potential evolutions due to climate change. Overall, this hierarchical map can be regarded as a useful tool for anticipating and prioritizing the needed retrofit actions, including remediation and preventive conservation strategies.

In conclusion, the paper demonstrated that building structural analysis and thermal-energy assessment tools and procedures may be effectively combined in order to identify their mutual interaction in affecting cultural heritage vulnerability due to climate change related events, by providing a more exhaustive assessment procedure able to take into account the synergistic effect of both these actions.

Conflict of interest

The authors declare no conflict of interest of this reviewed paper as well.

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